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SPACE WEATHER PREDICTION

Carl John Henney, et al.

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Final Report

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14. ABSTRACT

This final report represents a summary of the 6-2 In-House Work Unit (IHWU) 1010RDA1 activity for the period of 1 October 2007 (FY08) through 30 September 2014 (FY14) for AFRL/RVBXS. Members of the AFRL/RVBXS section have broad and deep expertise in observation, analysis, and modeling of solar and heliospheric processes and variability, which is leveraged though collaborative efforts with solar scientists in government, industry and universities. The work unit conducted applied research in support of the AFRL Focused Long-Term Challenge (FLTC) 2.6.3 "Integrated Space Environment Forecast Model." It specifically addresses the goals of the FLTC Product 2.6.3.1, "Solar Storm Forecasting". The following seven technical projects were identified as the applied research efforts during the duration of this work unit: 1) Solar Energetic Particle (SEP) Forecast Model; 2) Validated Sunspot Number Series; 3) Medium-term Forecasts of Major Eruptions; 4) Solar Flare Prediction Model; 5) Long-term Solar Wind Reconstruction; 6) Next Generation Solar Wind Model; and 7) Forecasting F10.7 and Ultraviolet Irradiance.

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1 INTRODUCTION

This final report represents a summary of the 6-2 In-House Work Unit (IHWU) 1010RDA1 activity for the period of 1 October 2007 (FY2008) through 30 September 2014 (FY2014), for AFRL/RVBXS. During the seven years, RVBX scientific personnel involved were Richard Altrock, Nick Arge, Don Norquist, K. S. Balasubramaniam, Edward Cliver, Rich Compeau, Misty Crown, Carl Henney, Janet Johnston, Steve Kahler, Stephen White, and Shawn Young. RVBXS administrative support was provided by RVBXS Program Manager Richard Radick. Two National Research Council post-doctoral appointees whose salaries were paid with external funding, Christina Lee and J. Lewis Fox, also contributed to the work unit technical efforts.

Members of the AFRL/RVBXS section have broad and deep expertise in observing and modeling of solar and heliospheric activity, which is leveraged though collaborative efforts with solar scientists in government, industry and foreign and national universities. The 6.2 IHWU "Space Weather Prediction" conducted applied research in support of the AFRL Focused Long-Term Challenge (FLTC) 2.6.3 "Integrated Space Environment Forecast Model." It specifically addresses the goals of the FLTC Product 2.6.3.1, "Solar Storm Forecasting".

The following seven technical projects were identified as the applied research efforts during the duration of this work unit: 1) Solar Energetic Particle (SEP) Forecast Model; 2) Validated Sunspot Number Series; 3) Medium-term Forecasts of Major Eruptions; 4) Solar Flare Prediction Model; 5) Long-term Solar Wind Reconstruction; 6) Next Generation Solar Wind Model; and 7) Forecasting $F_{10.7}$ and Ultraviolet Irradiance. There is some synergetic overlap of the efforts reported here as 6.2 applied research with 6.1 basic research efforts.

2 BACKGROUND

The IHWU results described here align with and directly support all three prongs of the 6.0 Space Situational Awareness (SSA) Technical Area Plan (TAP), viz: (1) Environmental monitoring capabilities (both ground- and space-based), (2) Assimilation and reporting of space weather conditions and events, and (3) Predictive and climatological models linking the space environment to system effects and impacts. Because the Sun is the principal source and driver of disturbances in the space environment, Space Situational Awareness requires understanding and predicting solar and interplanetary phenomena. The approach is to develop and improve the solar and interplanetary components of both empirical and physical space weather models, and to develop and improve the space- and ground-based data necessary to drive these models. More specifically, the goals are: to improve solar wind forecast models; develop 3-D heliospheric propagation models; improve solar energetic particle forecast models; improve statistical and empirical flare forecast models; develop physics-based flare models; develop 3-D fluid coronal models; and develop solar irradiance forecasting models. This work exploited space-based data (e.g., Solar Mass Ejection Imager - SMEI, Solar-Terrestrial Relations Observatory - STEREO, Solar Dynamics Observatory – SDO), and ground-based data (e.g., Global Oscillations Network Group - GONG, Vector SpectroMagnetograph - VSM, and the Improved Solar Observing Optical Network - ISOON).

3 METHODS, ASSUMPTIONS, AND PROCEDURES

The primary objective of the work unit was to improve predictions of the full range of solar emissions (electromagnetic, high energy particles, and plasma) on time scales ranging from hours/days to months/years depending on the nature of the emission. The goal of improved forecasts is to increase space situational awareness to mitigate the impacts of these emissions on Department of Defense systems operating in, or dependent on, the space environment. The approach applied to achieve the primary objectives was to develop the key instruments, observations, decision aids, and models needed to predict solar and solar wind disturbances on time scales of interest for space situational awareness.

The variety of solar emissions and the large range of time scales involved necessitated a multi-faceted approach. For example, probabilistic medium range forecasts of flares can be based on the daily observation of active region parameters, while specific short-term forecasts of flares is expected to require very high-cadence monitoring, high-confidence pattern recognition, and accurate physics-based models. Furthermore, short-term alerts of solar energetic particles (SEP) events based on flare parameters should be feasible since non-relativistic SEPs travel slower than the speed of light and take a finite time to exceed an intensity threshold of operational interest at Earth. Because of the long time scale (typically 1-3 days) for geoeffective plasma disturbances associated with Coronal Mass Ejections (CMEs) to reach Earth, geomagnetic storm forecasting can be achieved by remotely sensing solar wind disturbances en route to Earth such as demonstrated by the Solar Mass Ejection Imager (SMEI) or proposed by various radio-based techniques. Detailed modeling of the propagating disturbances (updated by remote and *in situ* observations) through the modeled ambient solar wind is required to produce accurate forecasts. Long-term forecasts of solar activity are thought to require measurements of solar polar fields, recognition of active solar longitudes, knowledge of long-term solar and solar wind behavior, and the use of solar dynamo models.

4 RESULTS AND DISCUSSION

For each of the seven technical project areas listed in the introduction for this work unit, the following subsections outline general findings and discuss results during the seven year effort.

4.1 Solar Energetic Particle (SEP) Forecast Model

During FY2008 and FY2009, a study was initiated to validate a recently published claim, by McCracken [1], finding a correlation between enhanced SEP event frequency or energy and a decreased heliospheric magnetic field. The evaluation found no support for McCracken's claim in auxiliary records of the period studied. In addition, the proposed physical model to explain the claimed correlation was also examined and found to be infeasible. The validation results are published in [2, 3]. In addition, a study was conducted to see if signatures of heliospheric SEP events could be detected through remote sensing. The first investigation considered gamma-ray emission from high energy ($E > 300$ MeV) ion collisions with solar wind ions. This research effort found that such emission might be detected for very energetic SEP events [4, 5]. Furthermore, a description of aSEP short-term warning model and its performance in preliminary evaluation was completed. This model inputs soft x-ray and 1 MHz integrated intensities, along with flare location. It outputs the probability of an impending SEP of greater than 10 MeV [6].

During FY2010, analysis of impulsive flares and ground level particle events (GLEs) to look for a role for flares in the production of high energy (> 100 MeV/nuc) particles was completed. In collaboration with Allan Tylka of NRL, measured elemental abundances in GLEs were used as the basic parameters for the comparisons. No evidence was found for a direct flare contribution to GLEs. While flare contributions cannot be ruled out, we suggest that the inverse correlations of Fe/O and e/p ratios with flare time and size scales is the result of a scaling between coronal mass ejection (CME) widths and flare time scales [7]. A study of galactic cosmic rays (GCRs) that provide the background above which SEPs are observed was done in FY2010. The study of GCRs is important because they are modulated over the solar cycle and on longer time scales. Findings on the solar drivers of 11-yr and long-term cosmic ray modulation, in which it was pointed out that a floor in the solar wind magnetic field strength, implies a ceiling in GCR intensity [8].

During FY2012, a study was conducted with N. Gopalswamy of NASA to see if SEP events originating in CME-driven shocks show variations attributable to coronal hole (CH) deflections of the CME trajectories. No systematic CH effects on SEP event intensity profiles were found. Furthermore, evidence of correlation between the CME leading-edge measured position angles and SEP event properties was not discerned, suggesting that the widths of CME-driven shock sources of the SEPs are much larger than the CMEs. Independently of the SEP event properties, the study did find evidence for significant CME deflections by CH fields in these events [9]. In addition, an investigation was done regarding the Kiplinger effect and determining a relationship between solar magnetic field changes and flares and particle acceleration. The Kiplinger effect is an observed association between SEP events and a soft-hard-harder (SHH) x-ray spectral evolution during the extended phases of the associated solar hard X-ray flares. The Kiplinger effect, besides its possible use as a space weather predictor of SEP events, has been interpreted as evidence of SEP production in the flare site itself, contradicting the widely accepted view that particles of large SEP events are predominately or entirely accelerated in shocks driven by coronal mass ejections (CMEs). Several ambiguities were found in the determination of whether and when the SHH criteria are fulfilled, which must be quantified and applied consistently before an SHH-based predictive tool can be made [10].

RVBXS contributed to a study of the feasibility of using SEP events as evidenced from nitrate concentrations in polar ice cores or radionuclide concentrations as a proxy for flare energies for a long-term frequency distribution of extremely energetic solar events. The work found that there is at most about a 10% chance of a flare larger than about X30 in the next 30 years. These findings were published in [11].

During FY2013, a study of the dependence of intensities and time scales of gradual solar energetic particle (SEP) events at 1 AU on the characteristics of the large scale coronal and interplanetary structures of coronal mass ejection (CME)-driven shocks was conducted. The work showed that the presence of a coronal hole directly between the sources of the CME and of the 1-AU magnetic connection was ruled out as an important factor. Second, there were no variations of the SEP events among different solar wind (SW) stream types: slow, fast, and transient. Finally, the separations between CME sources and CH footpoint connections from 1 AU determined from four-day forecast maps based on Mount Wilson Observatory and the National Solar Observatory synoptic magnetic-field maps and the Wang-Sheeley-Arge model of SW propagation were considered. Within the limited sample and the three analytical treatments, no statistical evidence for an effect of CHs on SEP event peak intensities, onset times, or rise times was found. These findings were published in [12].

A comparison between CME properties (masses, speeds, and energies) and theproperties of western hemisphere SEP events was completed. It was found that despite considerable scatter in the SEP and CME data, the large dynamical ranges of both the SEP and CME parameters allowed a determination of statistical trends in the comparisons of the logs of the parameters. The peak proton intensities at 2 and 20 MeV, Ip2 and Ip20 respectively, along with the total energy of the SEP event, Esep, are significantly correlated with CME kinetic energies, masses, and speeds, while the proton power law energy index γ trends lower (harder). Those correlations are higher with the leading edge CME speeds than with the center-of-mass parameters, indicating a less significant role for the body of the CME than for the CME front in SEP production. The high ratios (~10%) of Esep to CME energies found by Mewaldt et al. (2008) are confirmed, and the fits are consistent with a linear relationship between the two energies. The 2 MeV nuc^{-1} H/He ratios decrease with increasing CME speeds, which may be an effect of shock geometry. These findings are published in [13].

CME speeds and source longitudes were compared with solar energetic particle (SEP) timing characteristics from an updated list of SEP-CME events from solar cycle 23. Three timescales of 20 MeV SEP events were defined and related to speeds V and widths W of their associated CMEs observed by LASCO/*SOHO*. The timescales of the EPACT/*Wind* 20 MeV events are: TO, the onset time from CME launch to SEP onset; TR, the rise time from onset to half the peak intensity (0.5Ip); and TD, the duration of the SEP intensity above 0.5*I*p. This work was a statistical study based on 217 SEP–CME events observed during 1996–2008. The large number of SEP events allowed the examination of the SEP–CME relationship in five solar-source longitude ranges. In general, statistically TO declines slightly with V, and TR and TD increase with both V and *W*. TO is inversely correlated with log Ip, as expected from a particle background effect. It was found that a background-independent parameter TO+TR also increases with V and *W*. The correlations generally fell below the 98% significance level, but there was a significant correlation between V and *W* which rendered interpretation of the timescale results uncertain. The results suggested that faster (and wider) CMEs drive shocks and accelerate SEPs over longer times to produce the longer TR and TD SEP timescales. These findings are published in [14].

A study was done to determine the properties of the size distribution of SEP events, where it was found that the energetic proton events show a flatter size distribution than elections. The results suggest that the flatter size distribution of solar energetic proton (SEP) events relative to that of flare soft X-ray (SXR) events is primarily due to the fact that SEP flares are an energetic subset of all flares. These results are published in [15]. A subsequent study was done to relate the intensity of solar flares and their association with energy levels of the corresponding SEP events. A further analysis of the scaling law relationship was carried out and published in [16], where four arguments were presented against the idea of a direct nonlinear physical connection between the processes producing the flares and those producing the SEP events. First, a true scaling must relate SEP events to all flare X-ray events, and not to a small subset of the X-ray event population. It was shown that the assumed scaling law is not mathematically valid and that although the flare X-ray and SEP event data are correlated, they are highly scattered and not necessarily related through an assumed scaling of the two phenomena. An interpretation of SEP events within the context of a recent model of fractal-diffusive self-organized criticality provides a physical basis for why the SEP distributions should be flatter than those of solar flares. These arguments provide evidence against a close physical connection of flares with SEP production.

Beginning in FY2013, work was done to respond to a Space Weather Forecasting Laboratory (SWFL) initiative on SEP now-casting & forecasting in support of AFWA space weather operations. The goal was to provide three timescales of SEP forecasting for the SpEAR (Space Environment Anomaly Resolution) effort. The first timescale of interest is a 24-hr advance forecast of SEP events exceeding 10 pfu (pr cm^{-2} sr^{-1} s^{-1}) based on magnetic field measurements of solar active regions. The model developed by Dr. David Falconer of MSFC calculates a free energy proxy for all active regions observed on the disk to make the forecast of a >10 pfu SEP event. The second timescale is a forecast of imminent SEP events based on solar X-ray flare observations, using a model developed for use at NOAA by Dr. Chris Balch thatpredicts both the probability of a 10 pfu SEP event occurrence and the event peak intensity and rise time. Validation of the model is on-going at AFRL and NOAA. A third timescale of interest is the realtime forecast of rise time and peak intensity of a SEP event when the SEP onset has been detected, however, this work is expected to begin outside of time period of this work unit. The plan is to validate and implement each of these schemes into the SpEAR system.

During FY2014, two studies were completed to determine the effects of prior CMEs and the ambient corona on SEP event intensities. The possibility that SEP peak intensities, Ip, are enhanced by interactions of their associated CMEs with preceding CMEs (preCMEs) launched during the previous 12 hours was tested. The study found that the 20 MeV Ip of all the preCME groups correlated with the 2 MeV proton background intensities (and consistent with a general correlation with possible seed particle populations), plus the fraction of CMEs with preCMEs increases with the 2 MeV proton background intensities. The interpretation is that the higher SEP Ip values with preCMEs may not be due primarily to CME interactions, such as the "twin-CME" scenario, but are explained by a general increase of both background seed particles and more frequent CMEs during times of higher solar activity. However, the findings undermined the popular version of interacting CMEs as the cause of larger SEP events. The interpretation and relevance of CME interactions for larger SEP event intensities remains unclear [17]. The second study compared three kinds of background solar wind types with SEP events and found enhanced peak SEP intensities in transient solar wind streams [18]. The results suggest that monitoring low energy protons and solar wind stream properties at 1 AU could provide better SEP event forecasts. Additionally, SEP forecasts are guided by the observed/inferred limits of solar proton events. A study of the great solar-terrestrial event of August-September1859 [19] yielded a >30 MeV proton fluence of ~10^{10} pr cm^{-2}, about twice that for the August 1972 series of events. But the uncertainty is such that the 1859 peak intensity in this energy range could have ranged from 10^9 to 10^{11} pr cm^{-2}.

4.2 Validated Sunspot Number Series

The sunspot number (SSN) series validation work is driven by the existence of two disparate sunspot number series (the International SSN and the Group SSN) that have been used extensively as measures of solar activity dating back to 1610. The two SSN series diverge significantly during the 19th century, with no consensus as to which is correct. Thus, the SSN becomes a free parameter in studies of the solar dynamo, space climate, and terrestrial climate change. This is clearly an unacceptable situation. The goal of the work outlined in this section was to understand and reconcile the differences between the two SSN series by conducting a thorough review of the input data and construction procedures for each series and using auxiliary long-term indictors of solar activity such as geomagnetic observations to corroborate the final reconciled time series. For periods where geomagnetic data exist in the past (with some uniformity back to ~1840 and sporadically for about 100 years before then), the geomagnetic record can be used to verify the new reconstructed SSN series.

To achieve the goal of SSN reconciliation, four international workshops were co-organized by RVBXS, the National Solar Observatory (NSO), and the Royal Observatory of Belgium (ROB). The first workshop was conducted at NSO, Sacramento Peak, in September 2011. The 2nd workshop was held at ROB in Brussels in May 2012. Then RVBXS hosted a mini-workshop on this topic in September 2012 at Sacramento Peak and co-hosted the 3rd Sunspot Number Workshop in January 2013 at NSO, Tucson. During this 3rd workshop the reconciliation of the Group and International SSNs was completed for the interval from 1826-1980 and an inhomogeneity was uncovered in the 1981-present series. The 4th and final SSN Workshop was held in Locarno, Switzerland in May 2014. This workshop was hosted by Specola Solare Ticinese and Istituto Ricerche Solari Locarno. A preliminary version of the complete (1610-2013) revised SSN series was presented for the first time at the Locarno workshop. Publication of the new sunspot number time series, which will then become the official series for the solar and solar-terrestrial scientific communities, is tentatively planned for late FY2015. The end product of this effort will be a community-vetted standard SSN series, with stated uncertainties. A paper summarizing the results of the first two SSN workshops was published in the Central European Astrophysical Bulletin [20] and a second that will include the preliminary results of the full workshop series will be submitted to the same journal. Recently, a detailed paper [21] paper on the SSN reconciliation effort was published in Space Science Reviews.

In collaboration with co-investigators, a SSN prediction for cycle 24 was formulated. The forecast methods investigated were based on using the asymmetry of the ascending and descending solar cycle phases as a proxy for the future cycle, correlating the SSN between the maximum and minimum values for each cycle, and an autoregressive moving average model. The prediction for solar cycle No. 24 is that it will be weaker than the last cycle, No. 23. This work is published in [22].

In conjunction with the effort to recalibrate the SSN, during FY2010, a project was initiated to automatically measure sunspot area, irradiance deficit and sunspot number using ISOON 5-minute cadence continuous imaging of the Sun. This provides an opportunity to test the feasibility of measuring the sunspot numbers automatically. Current Zurich and International Sunspot numbers are obtained only once a day, however, we know that sunspots change in area and visibility through the day. Tracking these changes is expected to help in better forecasting the solar activity. Issues of concern include, for example, changing "seeing" conditions that impact visibility, de-projection effects, and dust specks due to improper flat-fielding. The results of applying the algorithm to past ISOON images and determining sunspot number in an automated manner were compared with archived subjectively-derived sunspot number records. The comparison revealed significant variability and showed that further work is needed to improve the consistency of these measurements.

4.3 Medium-term Forecasts of Major Eruptions

The forecast of major eruptions, on time scales of a month or two, was originally driven by anecdotal evidence that indicated that the increases in the solar wind magnetic field strength, and its association with coronal brightness, may provide a one- to two-month warning of the occurrence of groups of major solar eruptions. To begin to quantify a predictive relationship with the corona and major eruptions, torsional oscillation (TO) data was acquired from the Global Oscillation Network Group (GONG) and the Mt. Wilson observatory and used to analyze their relationship with solar corona activity. Long-lived brightenings in the corona are of interest and have been observed to propagate from near the solar poles to the equator over similar time scales as TOs (that is, solar-cycle time scales). In collaboration with Dr. Howe (NSO) and Dr. Ulrich (UCLA), the relationship between TO as observed on the solar surface and in the convection zone and brightenings in the corona was investigated. We found that there is an apparent connection between these two phenomena that extends from the equator to latitudes as high as 70° to 80°. This may imply control of both of these phenomena by the driver of the solar cycle (the solar dynamo) and thus place observational constraints on dynamo models [23].

During FY2009, daily observations of the corona were obtained in Fe X, Fe XIV and Ca XV with the Emission-Line Coronal Photometer (ELCP), weather permitting, and made publically available on the NSO web site for use by researchers and forecasters. Monthly coronal output was produced, reviewed, corrected as needed and provided to the NOAA National Geophysical Data Center for publication in *Solar Geophysical Data (Electronic)*. Work was done to ensure that all of the coronagraph and ELCP components were properly maintained. The coronagraph field mirror was realigned, and other optical components were serviced as required. These efforts ensure continued flow of coronal and prominence-magnetic-field data.

Additionally the NSO (Sacramento Peak) coronagraph was prepared for operation by High Altitude Observatory (HAO) personnel in a 2-week Prominence Magnetometer (ProMag) observing run during FY2009. Final repairs were completed by NSO, the owner of the coronagraph. The HAO's ProMag was successfully deployed in August 2009. The objective of ProMag is to determine, at the highest possible resolution, properties of solar prominences which lead to instability and eruption. The goal of this research is to improve the capability to predict prominence eruptions and the ensuing coronal mass ejections. The ProMag is a spectro-polarimeter, consisting of a dual-beam polarization modulation unit located at the prime focus of the NSO Evans Solar Facility (ESF) coronagraph, and of a spectrograph permanently set up on the ESF East Bench feeding a visible camera and an infrared camera. The instrument is designed to measure magnetic fields in solar prominences by simultaneous spectro-polarimetric observations of the chromospheric He I lines at 587.6 and 1083.0 nm (off-limb mode) or of H-Alpha at 656.3 nm and He I 1083.0 nm (on-disk mode). The spectrograph was deployed in March 2008. The ProMag polarization modulator was completely redesigned and thoroughly tested in the laboratory in the first half of 2009. Preliminary calibration data taken during the deployment run confirmed a high modulation efficiencies (within spec of predicted design) attained by the polarimeter.

In the first quarter of FY2010, Roberto Casini and Steve Tomczyk of NCAR/HAO visited Sunspot for an observing run with ProMag. During the run, a problem with the image position when transferring from the coronal photometer to ProMag was diagnosed and fixed. Calibrations of coronal photometer filters were performed by Lou Gilliam and John Cornett. During this procedure, Lou noticed a bright spot on the coronagraph O2 lens, which he attributed to an oil pool caused by separation of the lens elements. He and John Cornett fashioned an annular mask that covers the outer edge of O2, where the pool is located. Scans since the installation of the mask have been excellent, bringing closure to the source of the poor coronal scans that had plagued observations for the past two years.

Daily observations of the corona were obtained in Fe X, Fe XIV and Ca XV with the Emission-Line Coronal Photometer (ELCP), weather permitting. These data were made available shortly thereafter on http://nsosp.nso.edu/current_images for use by researchers and forecasters. Notifications of availability were emailed to interested parties simultaneously. Coronagraph optical components were serviced as required. These efforts ensure continued flow of coronal and prominence-magnetic-field data, which are required by MOUs and RVBXS in-house work units. A request was received from Chris Russell to publish results on the study of high-latitude coronal emission during this solar minimum in a paper he is writing for Reviews of Geophysics, "How Unprecedented a Solar Minimum". An article entitled "The Progress of Solar Cycle 24 at High Latitudes" was submitted and published [24].

During a planned observing run of ProMag during March 2010, operational problems led to the discovery of a crack in one of the wedges of the first Wollaston prism of the polarizing beam-splitter, due to a flawed design of the Wollastons leading to manufacturing errors resulting in stress and cracks from minor thermal loading. This required the ordering of new prisms. An extension of the National Solar Observatory (NSO)/HAO Memorandum of Understanding (MOU) for operation of ProMag for FY11 - FY13 was granted by the NSO Director. A problem concerning determining electronically the image position when switching ports on the coronagraph was solved. A broken cable and worn pulleys required to open the dome doors were replaced. These efforts ensure continued flow of coronal and prominence-magnetic-field data, which are required by MOUs.

On 20 Aug 2010, the ProMag optics were reinstalled in the spar at the ESF. A guiding problem delayed observations for several days but was finally diagnosed by John Cornett and other observatory technicians. A "work-around" allowed observations to begin, and a data set was obtained on 26 Aug. The ProMag team returned to Boulder on 27 Aug to begin data reduction and analysis. In order to avoid future thermal damage, a method was developed to provide continuous power to the thermal control system. Results of the ProMag data analysis revealed that the data were of lesser quality than that taken in March 2010. During this period, the RVBXS proposal entitled "An investigation of the physical properties of erupting solar prominences, phase 2" was awarded funding to hire a post-doc to assist in the acquisition and analysis of data from ProMag.

During solar cycle 24, observations of the Fe XIV corona from NSO (Sacramento Peak) site were found to show an abnormal spatial pattern compared to previous observations with the same instrument for Cycles 21, 22, and 23. The previous three cycles have shown a strong, rapid ”Rush to the Poles” in the Fe XIV emission, however, cycle 24 displays a weak and slow flow towards the northern hemisphere pole and may be indicative of the predicted weak activity for cycle 24 [25, 26].

During FY2011, the ProMag instrument was advanced in its performance, capabilities, and use. Early in the period, consultation with Roberto Casini and Greg Card at National Center for Atmospheric Research (NCAR) High Altitude Observatory (HAO) centered on focusing the aperture on the ProMag occulting plate at 6374 Å for our coronal scans. Dr. J. Lewis Fox was hired as a National Research Council (NRC) post-doc to conduct research on the ProMag. Dr. Fox and the HAO ProMag group began exploring changing the ProMag configuration, in response to a difficulty in aligning the two polarimeter beams on the entrance slit of the spectrograph. As a result of this analysis, the polarimeter package was placed on the optical bench in the observing room behind the spectrograph, instead of the previouslocation inside the coronagraph and Dr. Fox made progress on properly focusing the beam on the East Bench slit plane.

The ELCP coronagraph was active in research activities during FY2011, where coronal-scan processes and programs were upgraded to improve the usefulness of their output for space-weather forecasters and researchers. Routine coronal data acquisition, reduction, archival, and distribution and subscriber notification continued. Repairs were made to the coronal photometer 569.4 nm etalon heater. The O2 compound lens began to separate, causing bright spots in the field of view. Mechanical drawings of the lens and its mounting were obtained and turned over to the NSO lead engineer. Gary Poczulp of the National Optical Astronomy Observatory discovered that the CaF2 elements were severely degraded with dendrites, a brown circumferential stain, circumferential iridescent sheen and scratches. One of the four segments in one lens was phase-shifted from the other three. The brown stain and iridescent sheen were removed, and the scratches were thought to be the result of original polishing of the lens assembly. Index-of-refraction matching oil closest to that of CaF2 was acquired, which allowed Gary to complete reassembly and installation of the lens. The assembled lens was slightly thicker than before the repair process due to a buildup of thicker oil layers between the seven individual elements. As the excess oil seeps out over time the overall thickness of the lens will decrease. Tightening of the axial clips on the lens removed bubbles and voids in the oil and improved the condition of the lens. After installation in the coronagraph, new scans were conducted, ranging in quality from good to excellent. A new practice of keeping the light feed boxes sealed when not in use was adopted, to avoid moisture condensation damaging the CaF2 elements.

ProMag operations continued in FY2012 and involved data acquisition (including observations of a polar crown prominence) and calibrations (key to diagnosing/characterizing problems and alignment issues). Some progress was made on calibration theory and strategies for use with ProMag data both from the original configuration and from a new configuration. More work at the prime focus for ProMag configuration was completed. This resulted in transition to the new ProMag configuration with a re-balancing of the prime focus assembly, but the spar balance was not fully corrected. Testing of the ProMag O2 focus was conducted using the PixelVision visible camera within the O2 beam with a D3 yellow light filter and RG-850 band pass filter to allow only wavelengths greater than 850 nm. The infrared focus was found to precede the D3 focus by an amount comparable with independent findings. An image rotator was also added to the beam. Only a slight change in the focus was found to result. In the process of reconfiguring the ProMag, the driver computer failed to restart. The problem was corrected by the replacement of the motherboard. An attempt was made to realign ProMag in its new position on the optical bench. A new cable was fabricated for the relocated polarimeter. The polarimeter unexpectedly caused a deviation of the beam when it was put in the system between slit and collimator lens. During this period the instrument was sent to the High Altitude Observatory for repairs. It was determined that the Wollaston prisms in the polarimeter were not cut square by the manufacturer, and the only permanent fix was to acquire new ones. A workaround was instituted to keep the ProMag in operation in the meantime. The spectrograph was re-aligned with a laser source, and a corner-cube was used to help with aligning the image rotator. Some spectral images were acquired to check the performance and alignment of the spectrograph, during which an issue with the focus stage on the visible light camera which prevented achieving focus was identified and remedied.

Observations were made of the Venus transit with the ProMag and the Evans Solar Facility coronagraph. A definitive determination of size and orientation were made in observations. The final alignment and setup of ProMag was completed. The final alignment steps included resetting the cameras and grating to the ProMag helium channels (D3 and 10830) from the Venus transit wavelengths, and final focus of the cameras and collimator. Many details of the solar spectrum in these two regions are now visible, which before were obscured.

In addition, several problems occurred in the Evans Facility Coronagraph and support systems during FY2012, including obstruction of the lens guider, prime focus E/W drive motor failure, and development of a small air leak in the spar. Problems also developed with the handbox controls and the Instrument Control Computer (ICC), to which the handboxes are connected, leading to their total failure. After intensive effort, the problems with the ICC were resolved and it was restored to operation. This allowed observations of 15 distinct prominences by the ProMag over three days. Thirty-seven ProMag calibration measurements were also made during this time, using both the old and new procedures. Work continued on a new calibration procedure for the ProMag, including taking eight additional days of calibration data. The former deterministic calibration inversion code was changed to a more robust Monte Carlo inversion code. The previous calibration optics angular steps (45 and 22.5 degrees) were found to be sub-optimal. The modeling results suggested that angular steps of 15 and 60 degrees were close to optimal. Preliminary analysis of calibration runs with this new procedure suggested that it worked well and that the polarization efficiency of ProMag in the new configuration remained good.

Installation of a new calibration polarizer for the ProMag was considered. This new capability would increase the throughput of the instrument during calibrations, since the current polarizer cannot use the full aperture of the telescope. The installation of the new calibration optic would also improve the alignment of the calibration transmission axis. The calibration procedure is sensitive to this alignment and the current alignment was not known with high enough precision. A decision to proceed with a new calibration polarizer was postponed so that calibrations were not interrupted during the equinox season. Work began on the development of a new flat-fielding procedure for the ProMag measurements, which may allow flat-fields to be fast, semi-automated, and simultaneous with calibrations without much degradation in accuracy. In addition to speeding up operations, this allowed variations in flat-field over time to be tracked more successfully.

In the process of running the coronal photometer program, several bugs were discovered in the software that interfered with the correct operation of scripts. All but one was overcome, which is a continuing problem in the visible channel computer. The cause of the asymmetry and drift of the image ("spot") produced by the coronal scanning aperture located at the prime focus was identified. The spot asymmetry was caused by an obstruction in the beam produced by the recently-reinstalled secondary objective lens, O2. This was not expected to have an impact on coronal scans. The spot drift was caused by a misalignment of the coude-axis mirror that sends the solar beam into the observing room. All the necessary alignments of the telescope were addressed. An alignment strategy using a light source inside the telescope was envisioned. Parts for the coronal photometer aperture wheel to help recover the red focus were delayed. The necessary F1 clearance information was provided. Further refinement was necessary before a new mounting bracket for the aperture wheel could be designed. Another discovery was that the focus drive in the spar does not always go into its intended location. The focus drive stops between 3 and 8 inches above the hard stop at the bottom. Following the repair of the coronagraph O2 lens and lens apertures, experimentation with different values of the aperture for our coronal scans began. An asymmetry was found with the 16” aperture. This implies that the O2 lens repair was not completely successful, and that deformations still existed in the outer radii of the lens.

During FY2012, a study of the extended solar cycle activity was completed with observations in white-light coronagraphs and features seen in the Fe XIV green-line corona [5]. It was found that the coronal activity zones seen in the emission corona can be tracked high into the corona, and the peak latitude of magnetic and emission activity during solar maximum is found to be very similar for all heights compared. Additionally, the equator-ward drift of the activity bands were found to be faster at greater heights, and may imply that during the declining phase of the cycle, the solar wind detected near Earth is likely to be dominated by the next cycle. The so-called "rush to the poles" is also seen in the higher corona and found to start at a similar time but at lower latitudes than in the green-line corona [27].

During FY2013, calibrations were a major concern for ProMag. The runs now have at least twice as many calibrations as prominence runs (before and after each map) as well as other calibrations to help with an attempt to produce a complete model of the telescope during a given observation. Preliminary analysis of the calibration runs suggests that the new procedure works well and that the polarization efficiency of ProMag in the new configuration remains good (~50% in the Stokes parameters Q, U and V).

During observing runs with ProMag, it was found that the most important instrumental source of error is the alignment of the calibration polarizer. It has some offset angle, apparently in the range of 0.5 - 3 degrees, and this dominates the calibration error. The older calibration results can now be replicated using the current calibration code. Unfortunately, no information exists in the literature on the final design of ProMag (all published information is for the original design, which was never realized). This situation will be rectified in the final AFOSR report.

During FY2014, efforts continued on observations of prominences with ProMag, as well as the completion of processing code to analyze the observations in order to understand the mechanism by which prominences become unstable and erupt. Dr. Lewis Fox spent two weeks in January 2014 visiting with Roberto Casini (ProMag PI) and other scientists at HAO discussing calibration methods for ProMag. Dr. Fox gave a colloquium on the current ProMag calibration processing method. Dr. Fox’s calibration work continued throughout the year. Dr. Steve Tomczyk of HAO made some diffuser samples for use in the ESF coronagraph to produce flat-field images (since the ESF opal is too optically thick to serve this purpose). Dr. Fox tested the HAO-fabricated diffusers, but none had the necessary throughput. HAO procured a new "smart" diffuser from Luminit with variable transmission. However, this was not tested prior to the end of the work unit. NSO employee Timothy Henry, with help from Dr. Casini, officially took over responsibility for ProMag after the departure of Dr. Fox. Mr. Henry is a now a competent ProMag observer and data processer after his training by Dr. Fox. A large amount of data and calibrations were amassed by both Dr. Fox and Mr. Henry, however, no analysis of the data (producing physical parameters of prominences) occurred under this work unit. The work will continue under the auspices of HAO.

RVBXS continued in FY2014 to obtain coronal data, reduce and archive it, email it to subscribers, place it on the Sacramento Peak www and ftp sites, and notify other subscribers that the data were ready to be downloaded daily. We sent out CORONALERT emails describing the circumstances of our observations of Ca XV (only emitted by the most active solar regions) to our list of sixty interested recipients. As of late FY2014, analysis of solar coronal emission currently indicates that solar maximum in the northern hemisphere occurred in early 2012 (confirmed by hemispheric sunspot numbers), and a maximum is indicated in 2014 in the south. An analysis of coronal temperatures shows anomalously high polar temperatures at the minimum preceding Cycle 24 and anomalously low temperatures during the maximum phase of Cycle 24.

4.4 Solar Flare Prediction Model

During FY2008 and FY2009, it was decided that data sets from the AFRL/RVBXS ISOON (Improved Solar Optical Observing Network) prototype telescope and the National Solar Observatory Global Oscillation Network Group (GONG) instruments would be used initially to formulate predictor variables for the scheme, where the NOAA Geostationary Operational Environmental Satellite (GOES) X-ray flux measurements provided the predictand. The data sets were used to investigate the feasibility of using Principal Component Analysis (PCA) to parameterize the chromospheric variability (spatially) leading to flares. Several individual and collective active regions in the data set were investigated to determine their evolution and development leading to solar flares. The study sought to understand the chromospheric observations of erupting filaments and flares using the ISOON telescope data.

An in-depth study of solar active regions and associated flares of solar cycle 23 was conducted, beginning with the construction of a catalog of solar active regions (also known as sunspot groups) using data from the National Geophysical Data Center's Sunspot Group Reports section that were compiled from Air Force Solar Optical Observing Network (SOON) telescope sites, as well as several other international optical telescopes collecting data during the period 1997-2007. For each numbered active region, a table of its characteristics by observation date was constructed from the telescope data. Included in the active region characteristics were recorded H-alpha events as detected by the telescopes, as well as the X-ray flare events from the GOES X-ray sensors. This allowed the computation of the frequency of occurrence of at least one flare of each class. In addition, the frequency of occurrence of all flare events by flare class was computed. These two measures of occurrence frequency guided the formulation of the yes/no flare prediction technique and the flare magnitude prediction technique. The frequency distribution of these totals along with the frequency distribution of the number of flares per day and the intensity of the strongest flare were analyzed.

The development of a flare prediction technique using ISOON H-alpha images, using multiple discriminant analysis on principal components of a time sequence of ISOON images, was attempted to determine the validity of such a method. The principal components of ISOON images of six active regions with flares from solar cycle 23 were acquired to begin the development of the technique. Specifics of six flaring and six non-flaring sunspot groups were identified for initial solar flare prediction model (SFPM) development. An in-depth literature study of principal component analysis (PCA) was conducted and an implementation plan was developed for its use in the SFPM.

During FY2010, a study was initiated to analyze sunspot groups and Hα and X-ray flares reported for the period 1997 - 2007. Lists were generated of dates that sunspot groups were observed (designated sunspot group-days, SSG-Ds). For each SSG-D, a record for each associated Hα flare of importance category and for each X-ray flare of intensity C 5 or higher. The lists were analyzed to produce frequency distributions of SSG-Ds by year, sunspot group class, likelihood of producing at least one flare overall and by sunspot group class, and frequency of occurrence of numbers of flares per day and flare intensity category. It was found that only 3% of SSG-Ds produced a substantial Hα flare and 7% had a significant X-ray flare. For the period studied, fully developed and complex sunspot groups were found to be more likely than simple sunspot groups to produce a flare, though, in general, the latter were more prevalent than the former. Certain sunspot group classes are found to have flaring probabilities significantly higher than the combined probabilities of the intensity categories when all SSG-Ds were considered. For sunspot groups found likely to flare, a separate diagnosis of maximum flare intensity category appears feasible [28].

Upon further examination during FY2010, we found that using the eigenvectors to compute the principal components removes the temporal variability that is needed in the predictors used in the multiple discriminant analysis (MDA), therefore, elements of a subset of the eigenvectors corresponding to each ISOON measurement time was used as predictors in the MDA. A FORTRAN program was written to ingest eigenvectors, eigenvalues, and x-ray flux for a single flare event case in preparation for their use in MDA. Commercial off-the-shelf MDA software was identified, and an MDA Fortran code in use at AFWA was requested. A study of the nature of principal components of ISOON images before and after flares was conducted. It was found that the principal components classify the flares into two major categories, due to the underlying physics, rather than the traditional scale-based measurements. We suspect that the general physics of the post-flare situation is similar within all types of flares, but the underlying mechanisms leading to the flare appear to be very different.

GOES X-ray flux data at one-minute intervals was acquired from NOAA/NGDC for 12 additional ISOON active region observation cases. The discrimination (development) and classification (application) codes using Fisher's linear discriminant for two groups, our implementation of multivariate discriminant analysis (MVDA) on binary predictands (flaring vs. non-flaring), were modified to use a flare-no flare criterion based on a flux threshold set from the previous day's background flux. The development code to determine the discriminant vector coefficients and the application code to diagnose the probability of flaring were executed on eigenvectors/eigenvalues from all 18 ISOON observation cases. Based on the analysis, it was concluded that the technique should be tested with more extensive ISOON and GOES data sets, and compared with competitive discrimination and classification techniques, before attempting to extend it to forecast mode.

A study of the PCA for flare events as observed in ISOON imagery was conducted with summer intern Julie Stern. PCA data for 18 flares was analyzed, revealing that the principal components clearly show two kinds of flares, possibly with different underlying physical mechanisms. The first kind encompasses the weaker flares whose peak intensities in the X-ray scale range in the A-, B-, and C- class up to intensity 4.0 (based on the NOAA logarithmic scales). The second distinct class of flares encompass larger flares in the range of C8 and higher, including M- and X-class peak intensities. It was found that the principal components of all classes of flares are poorly correlated prior to a flare, however, the components are highly correlated after the flare. The post-flare similarities further suggest that the physical mechanisms of the post-flare loop formation are similar for all the flares studied.

During FY2011, a logistic regression algorithm to discriminate and classify the ISOON measurement time eigenvectors into flaring vs. non-flaring was tested and evaluated on 18 ISOON imagery sequence cases. This was done to provide a simple model baseline against which to compare the binary discriminant analysis approach developed in FY2010. The ISOON eigenvector regression study was expanded to more cases to more fully test the capability of the discriminant analysis and logistic regression techniques. Time series of eigenvalues, eigenvectors, and area-averaged image intensities were generated from Hα ISOON images for selected subregions of solar active regions between 2002 and 2006. These 27 new sequences were incorporated with the 18 previous sequences and used in the development and application of the multivariate discriminant analysis algorithm for flare probability estimation. The Hα area-averaged intensity time series from each ISOON sequence was considered as a suitable predictand, and an algorithm was designed to determine a binary flaring/non-flaring predictand based on a five percent or greater rise in area-average Hα. An additional criterion was that x-ray flaring must be occurring at the same times in order to set the predictand to flaring.

Preliminary results of using this approach showed that the binary flaring/non-flaring predictand based on a Hα rise threshold led to an inability of the discriminant algorithm to be able to distinguish between flaring and non-flaring times. This is thought to be due to an inconsistency between declaring flaring/non-flaring in the area-average Hα intensity and the trends in the corresponding eigenvectors, which act as predictors. So this approach was abandoned, and another predictand development scheme, called the Hα Magnitude Flare Characterization (HMFC) technique, was developed using multiple predictand groups and degrees of flaring to avoid an arbitrary on-off flaring threshold. A relationship between full disk mean intensity (FDMI) Hα / Hα(background) and whole disk x-ray flux (Xr) / Xr(threshold) in the form Hα / Hα(bg) = A + B log [(Xr) / Xr(th)] was developed from ISOON sequences in which these ratios had correlations > 0.7, where "background" refers to background value for the prior day to the analysis date, and the "threshold" is the next power of 10 higher than the prior day background x-ray flux. The NOAA SWPC "bkgd flux" algorithm was used to establish the background value for both Hα intensity and x-ray flux. The Hα / Hα(bg), Xr / Xr(th) relationship was used to set the boundaries for the flaring categories, such that when FDMI Hα/Hα(bg) is less than the value from the relationship when Xr = Xr(th), it is considered non-flaring, while if it has values within the range of Hα/Hα(bg) corresponding to the Xr/Xr(th) for x-ray flux flare classes, it is assigned to one of three flaring categories.

ISOON FDMI Hα time series for days prior to identified case dates were acquired and used to compute the background Hα intensity (Hα(bg)). Five-minute average Hα for the case dates was divided by prior-day Hα(bg) and correlated with five-minute average x-ray flux divided by the prior-day threshold value (Xr(th)). A linear least-squares best fit for the relation Hα/Hα(bg) = A + B log [Xr/Xr(th)] was found, and flare category boundary values were determined from standard X-ray flux flare class values of Xr. An algorithm to determine the discriminant vectors from multiple predictand groups, using Fisher's Linear Discriminant for Multiple Groups, was coded and tested. This was implemented in IDL code that ingested Hα and Xr for prior- and present-day files of selected training cases of ISOON image sequences, assigned each image time to a flaring category based on the category boundaries described above, and the Hα eigenvectors as predictors, and derived the discriminant vectors for each of the four flaring categories (none, weak, moderate, strong). These were then applied to eigenvectors from independent cases to diagnose the probability of each flaring category at each image time. Diagnosed probabilities of each flare category were compared with the specified category using the HMFC technique, and skill metrics were computed.

A new technique to designate multiple flaring categories, called the Hα Eigenvector Flare Categorization (HEFC), was developed in FY2011 and implemented in the multivariate discriminant analysis (MVDA) algorithm. This technique involves an a priori examination of the leading eigenvectors from each of the training ISOON imagery sequences. Distinct eigenvector characteristics place a given sequence into one of four flaring categories: none, weak, moderate or strong. This along with the X-ray flux time series for the same sequence, showing any flux rises that exceed the background flux and are accompanying by simultaneous rises in Hα intensity, are used to set a flaring level index indicative of the flaring category to be assigned for each flare. MVDA with HEFC was executed for three training sets of 10 sequences each, and resulting discriminant vectors were applied to independent sequences. Diagnosis of flare category probability was compared with HEFC-specified flare category at each observation time of the independent sequences, and skill metrics were computed. An in-house technical report manuscript was written describing the SFPM work from June 2010 to September 2011 and presenting the results of the earlier binary flaring diagnosis and the more recent multiple flare category diagnosis [29]. The technical report concluded with a recommendation for later extension of the study to apply the algorithms to data from the Global Oscillation Network Group (GONG) observatories and the Solar Dynamics Observatory.

The best version of the solar flare diagnostic algorithm to date, the Hα Eigenvector Flaring Characterization (HEFC) scheme, was trained on sets of 30 ISOON image sequences and X-ray flux time series, and the resulting discriminant vectors were applied to the other two sets of 30 sequences. The results showed too much overlap among the flaring intensity categories. The algorithm was changed to use 1-minute changes in the leading 10 eigenvectors as the predictors, along with the same changes in the X-ray flux as the basis for setting the predictand categories, removing the area averaged Hα intensity from determining the flare rise. The results showed improvements over the HEFC approach but the level of discrimination still was not satisfactory. Next, the solar flare diagnosis algorithm was modified to use the frequency distribution of all of the 1-minute changes for each of the leading nine eigenvectors in each image sequence as predictors. There were eight one-minute interval bins for each of nine eigenvectors, or 72 predictors for each ISOON image sequence. The predictand for the sequence was set by the shapes of the 9 eigenvectors and the peak X-ray flux, having a categorical value of 0,1,2,3 for non-, weak-, moderate-, and strong flaring. The modified MVDA code was executed on a set of 60 ISOON sequences to develop the discriminant vectors. So rather than diagnosing the flaring category for each 1-minute interval of each sequence, there is a single diagnosis of (maximum) flaring category for the entire sequence.

When the discriminant vectors were applied to the same 60 sequences, the discrimination into the four categories was perfect. However, when they were applied to the remaining 30 independent sequences, the discrimination was sub-optimal. After further analysis of the frequency distribution of all 1-minute eigenvector changes that make up the predictor vectors for this method from both development and application algorithms, it was determined that the category discrimination was unsatisfactory. The codes were modified to use only the 1-minute eigenvector changes before the flare rise in the X-ray flux to seek better distinction among the categories. Principal component analysis was applied to sequences of ISOON Doppler velocity for the same 90 dates and active regions used in the flare diagnosis algorithm for ISOON Hα intensity. It was clear that much of the variance was at higher frequencies for Hα, so that it was not feasible to represent the majority of the variance in the leading eigenvectors. An interim in-house report was submitted to DTIC, concluding that there was an insufficient distinction among the Hα eigenvectors of the four flaring categories to exploit them effectively in MVDA for either diagnosis or short-term prediction of flares [30]. The MVDA-based approach applied to Hα eigenvectors fell short of achieving a level of performance to consider it for possible technology transition as a solar flare prediction model. In the future, other solar measurements, pre-processing techniques and data-driven statistical methods will be investigated with the goal of achieving a suitable level of skill in short-term flare forecasting.

4.5 Long-term Solar Wind Reconstruction

Direct measurements of the solar wind exist only since the beginning of the satellite era (~1965). Additional knowledge of the long-term evolution of the solar wind is of interest to help enable mission planners set constraints on the expected range of future activity. Recent work on this topic was initiated in 1999, when a paper by Lockwood and co-authors [31] inferred that a doubling of the solar wind magnetic field had occurred during the 20th century. RVBXS and co-authors published a countering paper in 2005 [32], and a follow-on article in 2007 [33] proposing a "floor" on the magnitude of the solar wind magnetic field. It was argued that the solar wind magnetic field returned to Maunder Minimum-like conditions, if only briefly, at every 11-yr solar minimum.

The years 2007-2011 witnessed an emerging consensus in the results of independent research groups on the state of the solar wind (magnetic field strength and wind speed) during the past ~100 years [34, 35, 36, 37]. At the same time, it became necessary to revise the concept of the floor in solar wind magnetic field strength (B) in light of observations from space during the extended minimum at the end of solar cycle 23. In the new picture, the floor is lower, ~2.8 nT, compared to the previously reported ~4.6 nT, and, at 11-yr minimum, B consists of: the floor, a contribution from coronal mass ejections (CMEs), and a component that varies in concert with the solar polar magnetic fields [38]. A correlation between B at 11-yr solar minima and the peak SSN of the following solar cycle was used to construct a precursor relation based on inferred or observed B at the last 10 solar minima to predict a peak sunspot number of ~65 for cycle 24. This substantiated an earlier prediction based on direct polar field measurements for three solar cycles [39]. The notion of a floor in the solar wind, which has implications for the origin of the slow solar wind and the long-term variation of the galactic cosmic intensity, found support in the identification of a minimal magnetic state on the Sun during the extended solar minimum between cycles 23 and 24 [40, 41].

RVBXS participated in two International Space Sciences Institute (ISSI) Workshops on the Long-term Solar Wind. Both ISSI workshops (May 2012, and April 2013) were held in Bern, Switzerland. This effort will lead to two principal outputs: (1) a community-consensus paper on the variation of the solar wind magnetic field strength from 1800 to the present; and (2) a paper on the state of the solar wind during the Maunder Minimum (1645-1715). Following the April, 2013 workshop, RVBXS has worked (via e-mail and phone) with colleagues in the US, UK, and Australia to synthesize the results of the 16 person ISSI team on these two papers. The time series for solar wind magnetic field strength (*B*) is based on the sunspot number and geomagnetic indices as well as on direct observations during the space age. The 1800-present time series, which more than quadruples the period for which direct *in situ* observations exist, will be submitted for publication during FY2015. The new time series, and its comparison with a similar time series for *B* based on the more-difficult-to-deconvolve cosmogenic nuclide data (^{14}C and ^{10}Be), provide a bridge to >10,000 years of the solar activity record that is sequestered in tree rings and ice cores. The paper on solar wind conditions during the Maunder Minimum, the largest deviation in the solar record within the past 400 years, is based in part on thermodynamic MHD simulations of this intriguing epoch. It also will be submitted during FY2015. Here, as with the sunspot number reconstruction, the payoff for the Air Force is improved understanding and forecasting of the full range of solar activity and the resultant space weather.

4.6 Next Generation Solar Wind Model

During FY2008, this task was focused on two general activities: 1) improvement in the Wang-Sheeley-Arge (WSA) solar wind model, and 2) obtaining, learning to use, and working with components of the WSA+Enlil+Cone model. Much of the work was done in collaboration with Center for Integrated Space Weather Modeling (CISM) scientists and students from Boston University, University of California Berkeley, University of Colorado, and the NOAA/SWPC. Key improvements were made to the WSA model. The model now works almost exclusively with files in Flexible Image Transport System (FITS) format. All input files to the model are first converted into a FITS format with standardized WSA headers and file names. An extensive amount of information is provided in the file headers, which indicate the particulars of a model run such as grid resolution, empirical velocity formula used, source surface and outer coronal boundary radii, model version used, and much more. The switch to FITS file format has also allowed consolidation of the output generated by the model into a single file as opposed to the multiple ASCII format files (lacking adequate header information) that it originally generated. The new version of the model can be run using input data from virtually any solar observatory with minimal modification. It also provides standardized output files for use as input to the Enlil three-dimensional magneto-hydrodynamics (3D MHD) code. The new version of the WSA model is now running in near operational mode at NOAA/SWPC. In addition, the new code has also been delivered to the Community Coordinated Modeling Center (CCMC).

For several years Dr. Nick Arge (RVBXS) worked with and helped to mentor, in collaboration with her research advisor Boston University Professor Jeff Hughes, CISM graduate student Sarah McGregor. Nick is also serving on her thesis committee. Last year Ms. McGregor worked extensively with the WSA and WSA+Enlil models. Her improvement in the coupling of the potential field source surface (PFSS) and Schatten Current sheet components of the WSA model were outlined in [42]. During FY2008, McGregor worked extensively to improve the inter-calibration of the WSA and Enlil models. While the solar wind propagation component of the WSA model does account for effects due to stream interactions, it does not include all of the acceleration processes that occur in a full MHD version of the solar wind such as that due to the adiabatic expansion of the solar wind in which the thermal energy is converted into the kinetic energy. Thus the empirical relationship developed to predict solar speed using WSA exclusively tends to over-predict this quantity when it used in WSA+Enlil. To resolve this problem, McGregor used Helios spacecraft observations taken at 0.3-0.4 astronomical units (AU) distance from the Sun to improve the empirical WSA velocity relationship and thus provide better results with WSA+Enlil at the L1 point as well as far out of the ecliptic plane (e.g., by using the Ulysses spacecraft). This effort was part of her doctoral thesis work.

During the summer of 2008, Berkeley graduate student Christina Lee worked at AFRL (KAFB) as a Space Scholar. Her work was focused on performing a parametric study of CMEs launched into the inner heliosphere using the 3D Enlil numerical solar wind model together with the Cone model. The Cone model is a simple geometrical model that uses a cone shape to characterize the angular width and the central position of a halo CME. The main objectives of the work executed was to investigate and compare the sensitivity of the Enlil + Cone model to CMEs with varying densities, launch speeds and sizes, to small variations in launch direction, and to grid resolution when launched into an idealized ambient solar wind background at different locations with respect to the streamer belt. The properties of the interplanetary CMEs (ICMEs) arriving at 1 AU from different vantage points (including the Sun-Earth line), such as their shock strengths and propagation times, were also compared.

During FY2009, collaboration was begun with scientists at Prediction Science Inc. (PSI) on a joint NASA Living With a Star-funded effort to develop an advanced time-dependent background coronal and solar wind model. This effort includes coupling the advanced 3D magnetohydrodynamical (MHD) MHD Around a Sphere (MAS) coronal model and the coronal portion of the simpler Wang-Sheely-Arge (WSA) model to two solar wind models (i.e., the one developed by PSI and the Enlil code developed by D. Odstrcil). The group at PSI have incorporated the WSA model within their model code by modifying it so that the solutions to both the potential field source surface and Schatten current sheet models are calculated using their numerical solving scheme instead of the more traditional spherical harmonic expansion approach. Jon Linker (PSI) agreed to provide this parallel code, called CORHEL, which now includes WSA, MAS, the ENLIL 3D MHD solar wind model, and the PSI solar wind model. CORHEL is currently being installed on AFRL-Kirtland computer cluster.

RVBXS participated with NOAA/SPWC's plans to transition the WSA+Enlil+Cone model to operations. NOAA/SWPC will transition the WSA along with Enlil+Cone models, while AFRL will run an identical version of the model at KAFB where it would serve as a backup to the NOAA operational version. RVBXS is also available to answer questions and correct problems as needed. The parallel version of the Enlil code was provided by Dusan Odstrcil. The code was installed on the eight-node Zambia computer. Future collaboration with Dr. Odstrcil are planned. Also, the WSA code was reviewed in detail with Leslie Mayer of NOAA/SWPC to assist her in understanding the code both procedurally as well as scientifically. Ms. Mayer, as part of her contract work with AFRL, also provided a detailed update on all of the improvements she has made in the code, including a recent improvement in the method for tracing field lines. The WSA model software was made available to an RVBXS Space Scholar, Warner Meeks, to conduct a verification of forecasts in support of a SWFL project. A WSA user's manual was provided to Predictive Sciences Inc. as a part of a NASA grant effort. Captain Joe Reich of AFWA expressed interest in transitioning WSA into operations. It was concluded that the SWFL transition process be used. The WSA solar wind propagation code was modified to add the ability to keep track of the source regions (i.e., the latitude and longitude of the solar wind sources at the photosphere) of the solar wind observed at L1, as well as the photospheric field footpoint strength of the sources and other key parameters. This addition will allow the connection of the predicted speed at L1 with its source back at the Sun.

During FY2010, the Wang-Sheeley-Arge (WSA) coronal model was modified to accept gridded photospheric magnetic field maps generated by the Air Force Data Assimilative Photospheric Flux Transport (ADAPT) model [43, 44]. A number of test runs of the WSA coronal model were conducted using ADAPT maps and conventional magnetogram synoptic photospheric magnetic field maps. The results revealed important differences in the structure, location, and sizes of coronal holes between that obtained using traditional maps and the those from ADAPT. Possible involvement in efforts to transition the WSA+Enlil+Cone solar wind model into operations at the NOAA Space Weather Prediction Center was discussed with NOAA personnel, and a plan was formulated. Incorporation of the WSA coronal model in the CORHEL model of Predictive Science, Incorporated was discussed with company personnel.

The WSA code was modified to include density. Implementation of the best technique to physically account for density compressions and rarefactions in the solar wind kinematic model is continuing. Contributions were made to a study that attempts to better understand the sources/causes of the differences seen in the corona during the last two minima. In addition, during FY2010, an AFRL Space Scholar made a number of improvements to the WSA code, including the ability to routinely make daily updated WSA solar wind speed and IMF polarity predictions at the STEREO A and B satellite positions in their solar orbits. The WSA display graphical user interface (GUI) was modified to accurately display the sub-earth and STEREO A and B positions on the plots along with their associated date stamps.

During FY2011, the cone model fitting routine for simulating coronal mass ejections in a solar wind model was acquired from George Millward and Vic Pizzo of NOAA Space Weather Prediction Center (SWPC). Collaboration with SWPC personnel resulted in successful integration of the cone model in the Wang-Sheeley-Arge (WSA) coronal model +Enlil solar wind model suite for test and evaluation. The Enlil code was installed on AFRL computer systems with assistance from model author Dusan Odstrcil. This allowed the capability to run daily updated WSA+Enlil solar wind simulations with (or without) CMEs (via the cone model) included. A time assignment offset issue in the Enlil code was discovered, and consultation with Dusan Odstrcil confirmed its existence and method of solution. The solution was imposed and the correction was observed in the model output.

RVBXS collaborated with NSO personnel on the prioritization of tasks related to improvement of their SOLIS, KPVT, and GONG magnetograms and daily updated and Carrington synoptic maps for use in solar wind modeling at AFRL. Solar magnetograms are essential inputs for solar wind models, e.g., WSA. The recalibrated GONG magnetograms are targeted for use in initializing the extensive WSA+Enlil forecasts planned for execution and analysis. WSA results obtained from the newly calibrated pole corrected GONG Carrington maps were compared with those obtained using their older maps to validate improvement.

The WSA model was modified to include the coronal polarity source coordinates in the solar wind parcels propagated out to Earth. These coordinates have to be included so that the coronal sources of the WSA-predicted interplanetary magnetic field (IMF) polarity at 1 astronomical unit (AU) can be identified back at the Sun. In addition, questions from AFWA regarding differences in the versions of the WSA+Enlil+Cone solar wind and CME simulation models being used by NOAA/SWPC and the Coordinated Community Modeling Center (NASA) were addressed. AFWA noticed differences in the predictions involving CME forecasts, an investigation found that the two centers are running two different versions of WSA.

During FY2012, in collaboration with NOAA/SWPC, WSA was modified to use solar global photospheric magnetic field maps generated by the Air Force Data Assimilative and Photospheric Flux Transport (ADAPT) model as input. Progress was made on WSA upgrades such as using the Runge-Kutta 4th order method for tracing field lines from photosphere out into the corona and vice versa. A bug in the WSA model code that was producing inconsistencies between the calendar and Julian dates was found and corrected.

In collaboration with the AFRL Space Weather Forecasting Laboratory (SWFL), a new tool was developed called the WSA Coronal Analysis Tool (CAT), where WSA-CAT is a graphical capability that displays the coronal magnetic field produced by the WSA corona model, including depictions of magnetic field neutral lines at 5 solar radii superposed on solar images from current ground- and satellite-based instruments. WSA-CAT also shows the field line connection from Earth to prominent coronal holes apparent in the images. After successful development, WSA-CAT was prepared for technology transition to the Air Force Weather Agency (AFWA).

Another major focus during FY2012 was the use and improvements of the WSA+Enlil+Cone solar wind and coronal mass ejection (CME) propagation model. Discussions were held with V. Pizzo and G. Millward of NOAA/SWPC on the use of photospheric magnetic field maps from the ADAPT model as input. Ensemble modeling of CME propagation, work with Dr. Lee, was published on the methods for quantifying the uncertainty of CME arrival time forecasts using WSA+Enlil+Cone [45]. In addition, RVBXS personnel also contributed to providing contextual information about the solar wind properties and the interplanetary magnetic field (IMF) near flybys of Mercury by the MESSENGER spacecraft using the WSA+Enlil combined model. The WSA model utilized solar photospheric magnetic field observations in order to estimate the inner heliospheric radial flow speed and radial magnetic field (out to 21.5 solar radii from the Sun) which was used as input to Enlil to estimate the solar wind velocity, density, temperature, and magnetic field strength and polarity. Using WSA-ENLIL calculations in conjunction with available MESSENGER data, it was found that the solar wind conditions were very quiescent and would have provided only modest dynamic driving forces for Mercury's magnetospheric system during the flybys [46].

During FY2013, the work effort focused primarily on the: (1) modification of the WSA coronal and solar wind model so that it is fully compatible with the structure of the Air Force Data Assimilative Photospheric flux Transport (ADAPT) model output files; (2) general improvement of the WSA model; (3) automation of ADAPT at the National Solar Observatory (NSO); (4) Coronal Mass Ejection (CME) modeling and validation using the WSA-Enlil-cone model; and (5) development of a time-dependent WSA-Enlil solar wind model. Due to the complexity of the ADAPT model output files, significant changes to WSA were required before the ADAPT global maps could be used as input data. For example, unlike nearly all other photospheric magnetic field sources, the global ADAPT maps are in latitude-longitude format, as opposed to the more traditional sine-latitude-longitude format. This unique feature of ADAPT required that a key module (and associated subroutines) within WSA had to be changed. Originally, the module simply assumed all observatory input maps were in sine-latitude format and automatically converted them to the WSA required latitude format. The module was changed so that it now checks the format of the observatory input files first and skips the sine-latitude to latitude conversion step when the maps are already in latitude. The WSA code was also changed so that it now routinely adds a standard key word to the headers of all observatory input maps indicating which format (sine-latitude or latitude) they are in.

Another complicating aspect of the WSA upgrade to ingest ADAPT model output files is that the ADAPT FITS files are comprised of an ensemble of realizations representing the uncertainly of the global photospheric field, as opposed to the more traditional signal global map representation at a given time. Each ADAPT file also includes a binary table specifying the model parameters used to generate ensemble set of maps. The WSA software therefore had to be modified to accommodate these unique features of ADAPT, while also retaining its ability to ingest the file formats from solar observatories that it is already designed to work with. The approach decided upon for WSA is to keep the ADAPT realizations and associated binary table together, as a unit, in each of the (several) intermediate files generated by the code until it reached the stage in the program where the coronal solutions are run on the individual global maps (realizations). At this stage, the WSA code runs a separate coronal solution for each individual ADAPT map and then saves the output as a separate file with the realization number being added to the file name to distinguish it from the other ensemble members. The WSA output files used to drive Enlil are also generated as individual files (i.e., one file per model realization) with the pertinent binary table stored in each of them.

In addition to the ADAPT related changes described above, it was also decided to significantly change the file naming convention used by WSA. For more than a decade, WSA files were named using the following general convention:

> file type (int = interpolated, wsa=coronal solution, etc), Carrington rotation number, longitude of the leading edge of the map, version number, and observatory name.

For example, wsa_2071_289.00_01_gong.fits corresponds to the coronal solution output map having a leading edge with Carrington Rotation (CR) number and longitude coordinates of 2071and 289.00 degrees, respectively, and version number 01, which indicates that it is the first map generated with this particular combination of CR number and longitude. If subsequently another map happens to be created that has exactly the same combination of values, the code knows to increment its version number to 02 and so on. While rational, this naming convention has always made it hard to easily sort the WSA files in order of time, since Carrington longitude decreases with time. Also, one needs to be comfortable thinking in terms of CR number and longitude and also converting them to standard time. To simplify all this, a new file naming convention based on time was developed. The new system uses the following general convention:

> file type name (int = interpolated, wsa=coronal solution, etc), year, month, day, hour, minute, realization number, and observatory name.

For example, wsa_200501161803R009_ans.fits corresponds to the coronal solution output file (wsa) using the ADAPT NSO/VSM input map (ans) corresponding to a time and date of 18 hours and 3 minutes on January 16, 2005. R009 corresponds to the 9th realization of the ensemble set of model maps.

The WSA code was also modified so that the radial magnetic field values on a spherical surface positioned at or inside the Source Surface radius can be used to initialize the Schatten Current Sheet (SCS) model component of WSA. In Previous work by McGregor, it was shown that careful selection of a source surface radius and an inner radius (i.e., the one used to drive the SCS component of the model) minimizes the field line discontinuities that often arise at the traditional potential field source surface (PFSS)-SCS interface [42]. RVBXS, along with NOAA SWPC (Pizzo and Millaward), and George Mason University (Odstrcil), worked to modify the WSA-Enlil operational solar wind model so that it runs in a more realistic, time-dependent fashion. Specifically, Enlil was modified so that it continuously updates its inner boundary condition with new WSA output maps instead of running each one to steady state, as is currently done. Several sets of WSA-ADAPT test maps were provided by AFRL to SWPC and GMU to help with the development and testing of this aspect of Enlil. To facilitate the eventual use of ADAPT as a data feed to the operational WSA+Enlil model, ADAPT was installed, and work began to automate the code, at NSO using both VSM and (primarily) GONG magnetograms as the input to ADAPT. Incorporating GONG into ADAPT was a major effort requiring significant modifications to the ADAPT code as well as cumbersome retuning of ADAPT model parameters (e.g., north/south meridional drift rates).

To further develop and test the predictive capabilities of the 3D MHD WSA-Enlil-cone model and to better understand the complexities of interacting CMEs, the 2-4 August 2011 succession of three fast CMEs (> 600 km/s) were simulated. These CMEs were associated with M-class flares observed in NOAA AR 11261 that was located near disk center during this time. Possible scenarios for the evolution, propagation, and interaction of the CMEs (e.g., CME-CME and/or CME-stream) en route to Earth were explored by generating a modeling ensemble. Specifically, multiple sets of input parameters were created through the use of a cone fitting tool together with realistic ranges for the angular width and leading edge distance estimated from STEREO limb observations. An ensemble set of Sun-to-Earth modeling results were generated from the different combinations of input cone parameters for each of the three CMEs. Based on the ensemble of global 3D results and temporal profiles at 1 AU, it was concluded that at least two, perhaps all three, of these CMEs interacted en route to 1 AU. This conclusion was based on the consistency of the model time profiles with single-point in situ L1 observations. These findings are expected to be published during FY2015.

During FY2014, Dr. Nick Arge worked with Dusan Odstrcil (Enlil model developer) to begin time-dependent WSA+Enlil runs using ADAPT maps as its driver. ADAPT maps were tested in the WSA+Enlil model in the past, but in all previous cases, the model was driven to a steady using a single (i.e., non-updating) map. In FY2014, the WSA+Enlil model was driven with a continuously updating ADAPT photospheric magnetic field boundary condition. A 60 day period was studied ADAPT maps at a 2 hour cadence (generated from GONG magnetograms) for the February 15-April 15, 2012 time interval. Even though there were several CMEs during March 2012, overall, the model results (with the simulated CMEs included) agree reasonably well with observations. The model did not predict the solar wind speed during the latter part of the run (i.e., March 21-29), however, further investigation revealed that a far-side active region (not included in the ADAPT maps) was approaching the east limb during this period and was likely affecting the WSA coronal solutions used to drive Enlil. Once the active region appeared on the front side of the Sun and was thus integrated into ADAPT, the model and observations resumed with good agreement.

4.7 Forecasting $F_{10.7}$ and Ultraviolet Irradiance

Beginning in FY2011, a new method to forecast the solar 10.7 cm (2.8 GHz) radio flux, abbreviated $F_{10.7}$, was developed and validated. The unique method, a byproduct of the 6.1 AFOSR supported ADAPT project, utilizes predictions of the global solar magnetic field generated by the ADAPT flux transport model. Using indices derived from the absolute value of the solar magnetic field, we found good correlation between the observed photospheric magnetic activity and the observed $F_{10.7}$ values. Comparing magnetogram data observed within 6 hours of the $F_{10.7}$ measurements during the years 1993 through 2010, the Spearman correlation coefficient, r_s, for an empirical model of $F_{10.7}$ is found to be 0.98. Little change in the empirical model coefficients and correlations were found between the first and second 9 year intervals of the 18 year period investigated. By evolving solar magnetic synoptic maps forward 1-7 days, this new method provides a realistic estimation of the Earth-side solar magnetic field distribution used to forecast $F_{10.7}$. Spearman correlation values of approximately 0.97, 0.95, and 0.93 are found for 1 day, 3 day, and 7 day forecasts, respectively [47].

During FY2013 and FY2014, the F10.7 forecasting method was expanded to predict the solar irradiance of selected wavelength ranges within the extreme ultraviolet (EUV) and far ultraviolet (FUV) bands. As with the $F_{10.7}$ study, good correlations were found between the absolute value of the observed photospheric magnetic field and selected EUV/FUV spectral bands. Pearson correlation coefficient values of 0.99, 0.99, and 0.98 are found for 1 day, 3 day, and 7 day predictions, respectively, for the extreme ultraviolet band from 29 to 32 nm. For the Lyman-alpha line (at 121.6 nm), correlation values of 1.0, 0.99, and 0.98 are found for 1 day, 3 day, and 7 day predictions, respectively. In the far ultraviolet, for example the 160 to 165 nm spectral band, correlation values of 0.98, 0.97, and 0.96 are found for 1 day, 3 day, and 7 day predictions, respectively. Unlike the $F_{10.7}$ study, we found that observed integrated full-disk solar EUV and FUV signals are strongly correlated with the weaker magnetic fields associated with plage regions, suggesting that solar magnetic indices may provide an improved indicator (relative to the widely used F10.7 signal) of EUV/FUV non-flaring irradiance variability as input to ionospheric and thermospheric models.

The $F_{10.7}$ and EUV/FUV studies highlight how global magnetic maps can be used to improve forecasting of key space weather parameters. We expect to improve the modeling by including far-side helioseismic information of new flux emergence. In addition, no spatial weighting was included in this work for ultraviolet study even though center-to-limb intensity variations are expected for the various bands within the solar EUV/FUV range studied. Additionally, since the integrated irradiance of some of the EUV/FUV bands actually drops in intensity as a result of coronal hole regions, we expect to improve UV predictions by incorporating an estimate of the Earth-side coronal hole regions.

5. CONCLUSIONS

As outlined in this final report, the objective of this work unit was to improve predictions of solar emissions (electromagnetic, high energy particles, and plasma) on time scales ranging from hours to years depending on the source of the emission. Seven technical projects were identified and executed during the duration of this work unit: 1) Solar Energetic Particle (SEP) Forecast Model; 2) Validated Sunspot Number Series; 3) Medium-term Forecasts of Major Eruptions; 4) Solar Flare Prediction Model; 5) Long-term Solar Wind Reconstruction; 6) Next Generation Solar Wind Model; and 7) Forecasting $F_{10.7}$ and Ultraviolet Irradiance. Clear progress was made in numerous areas towards improved forecasting to help increase space situational awareness to mitigate the impacts of solar emissions on Department of Defense systems operating in the space environment.

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